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EVALUATION OF ACCELERATION-INDUCED PHASE NOISE  
IN SURFACE ACOUSTIC WAVE DEVICES

JOHN KOSINSKI, ARTHUR BALLATO, AND THEODORE LUKASZEK  
ELECTRONICS TECHNOLOGY AND DEVICES LABORATORY

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Stable local oscillators based on surface acoustic wave (SAW) resonators have been proposed for future use in Army electronic systems designed for airborne and vehicular applications. The vibration spectra of these systems in conjunction with the vibration sensitivity of the SAW resonators leads to a degradation in oscillator phase noise, which may then exceed the total allowable system phase noise. This report details a study of the vibration-induced phase noise in a group of SAW oscillators developed for a low-noise radar application.			
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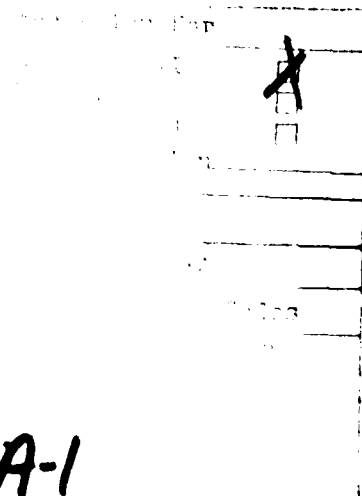
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## INTRODUCTION

Stable local oscillators based on surface acoustic wave (SAW) resonators have been proposed for future use in Army electronic systems designed for airborne and vehicular applications. The advantages of the SAW oscillator in such systems are reductions in size, weight, and power consumption due to the high frequencies (1 GHz or better) obtainable without the use of frequency multiplier chains. The small size and simplicity of SAW resonators leads to low-cost UHF oscillators with spectral purity superior to that obtainable using any other UHF frequency control device.

As with bulk acoustic wave (BAW) quartz resonators, SAW resonators are sensitive to external accelerations. The resonant frequency  $f_0$  of the SAW device experiences a perturbation  $\delta f$  given by

$$\delta f = f_0 (\Gamma \cdot \mathbf{A}) , \quad (1)$$

where  $\Gamma \cdot \mathbf{A}$  is the scalar product of the SAW device acceleration sensitivity  $\Gamma$  (a vector property of the SAW device) and the external acceleration field  $\mathbf{A}$ . Reported values for  $|\Gamma|$  for SAW devices range from  $10^{-8}$  per g (1g = earth's gravitational field) for single SAW devices to  $3 \times 10^{-10}$  per g for dual SAW device structures employing compensation techniques.

In this study, measurements of the acceleration sensitivities of a group of SAW resonators developed for a low-noise radar application are presented. The SAW resonator designs were systematically varied in order to obtain the best possible phase noise in a quiescent environment. In this report the relationships between the design changes and the vibration induced phase noise will be discussed.

## EXPERIMENTAL SAMPLES

The SAW devices used in this study have been extensively detailed elsewhere [1]. The experimental matrix included three device types (one-port resonator, two-port resonator, delay line), two metallization types (pure Al, Cu-doped Al), three transducer thicknesses (400Å, 600Å, 800Å), and three busbar thicknesses (2000Å, 6000Å, 10,000Å). Details of the experimental matrix are shown in Table 1. A total of twenty-two devices were tested, consisting of twelve each delay lines, one each one-port resonator, and nine each two-port resonators.

## TEST SYSTEM

A block diagram of the test system employed is shown in Figure 1. In the presence of a sinusoidally varying acceleration field, the output signal (carrier) of the SAW based oscillator will undergo frequency modulation at the sinusoidal frequency of

TABLE 1. EXPERIMENTAL MATRIX

Device Type	Transducers		Busbars
	Thickness (Å)	Material	Thickness (Å)
Delay Line	400	Pure Al	not reported
One-Port	600	Pure Al	2,000
One-Port	600	Copper doped Al ( $\approx 0.5\%$ )	2,000
One-Port	600	Pure Al	6,000 or 10,000
One-Port	400	Pure Al	2,000
One-Port	800	Pure Al	2,000
One-Port	600	Flash chrome ( $\approx 60\text{Å}$ ) + pure Al	2,000

the acceleration field. The effect is analogous to tone modulation and the ratio of the power in the  $n^{\text{th}}$  acceleration-induced sideband to the power in the carrier is given simply as

$$f_a^{(n)} = 20 \log [J_n(\beta)/J_0(\beta)] , \quad (2)$$

where  $\beta$  is the modulation index determined from

$$\beta = \frac{\Omega_0 (\Gamma \cdot \mathbf{A})}{\Omega_a} . \quad (3)$$

In equations (2) and (3),  $\mathbf{A}$  is the peak acceleration,  $\Omega_0$  is the unperturbed output frequency,  $\Omega_a$  is the acceleration frequency, and  $\Gamma$  is the acceleration sensitivity. If the modulation index is less than 0.1, equation (2) simplifies to

$$f_a^{(n)} \approx 20 \log \frac{f_0 (\Gamma \cdot \mathbf{A})}{2 f_a} . \quad (4)$$

We can therefore measure  $\Gamma$  by applying a sinusoidally varying acceleration field via a shaketable and measuring the power in the acceleration-induced sidebands using a spectrum analyzer. Inasmuch as  $\Gamma$  is a vector quantity, we perform the measurement along three orthogonal axes.

The limitations of the measurement system as implemented may be found by first solving equation (4) for  $\Gamma$  and then examining the sensitivity of the calculated  $\Gamma$  value to each of the measured quantities  $f_c$ ,  $f_a$ ,  $|\mathbf{A}|$ , and  $f_a^{(n)}$ . Errors in measuring the

sideband levels contribute

$$\frac{\delta\Gamma}{\Gamma} = 10(\epsilon/20) - 1, \quad (5)$$

errors in measuring the acceleration frequency contribute

$$\frac{\delta\Gamma}{\Gamma} = \frac{\epsilon}{f_a}, \quad (6)$$

and errors in measuring either the peak acceleration or carrier frequency contribute

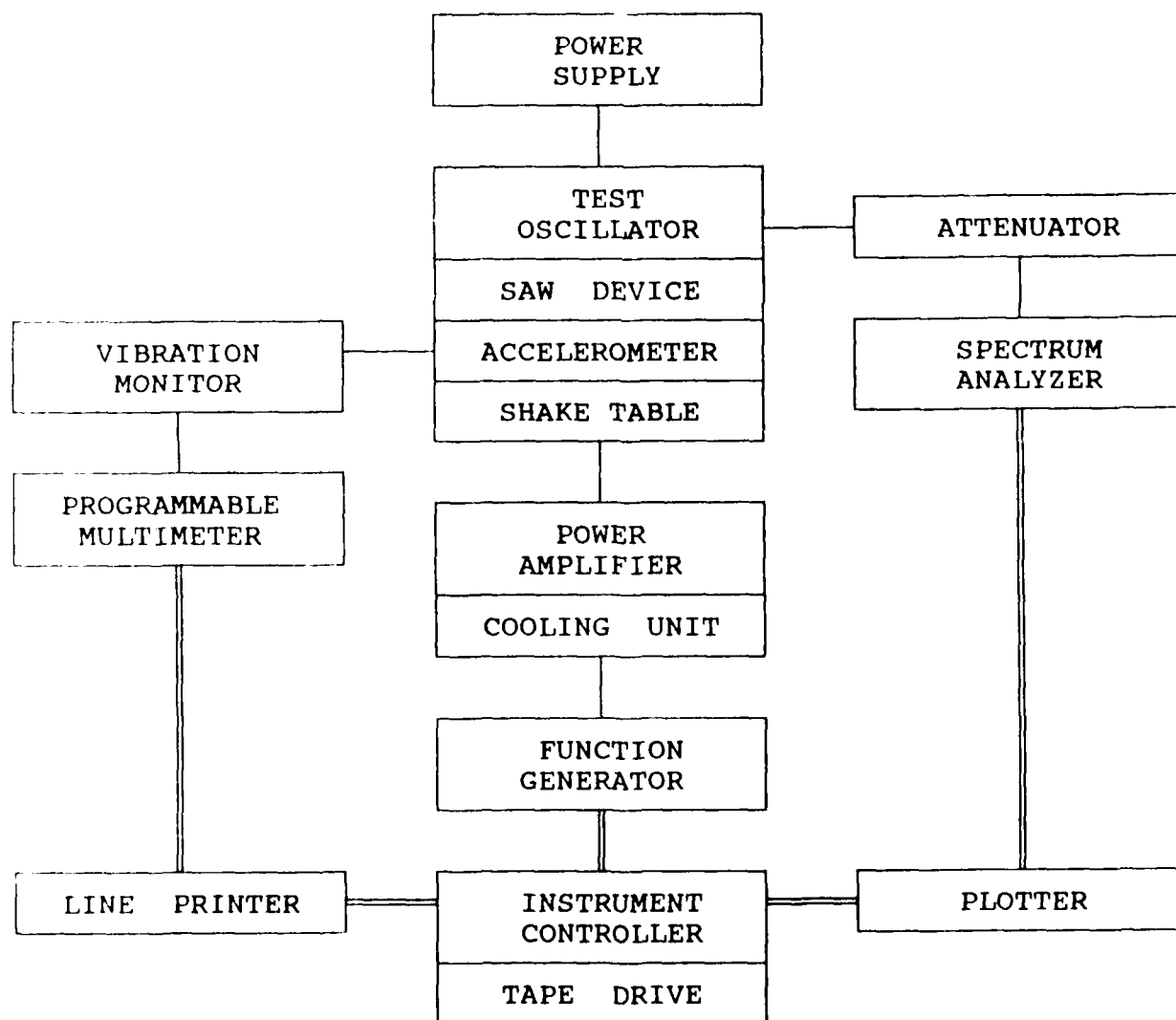


Figure 1. Test system block diagram.

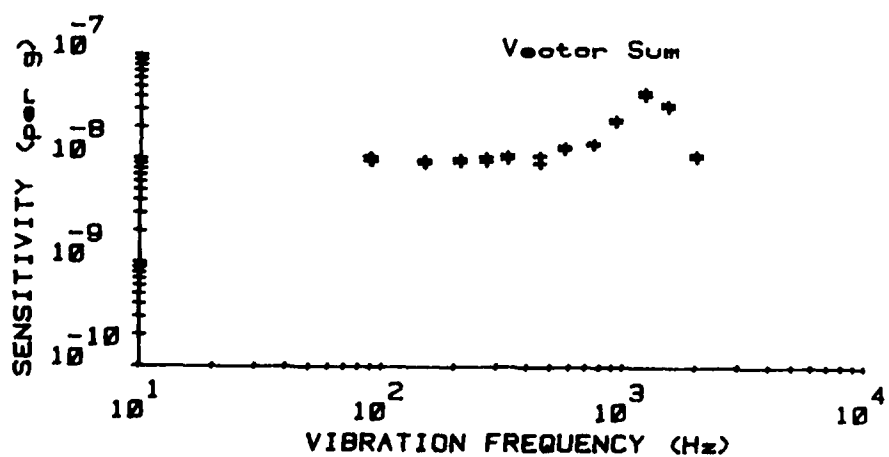
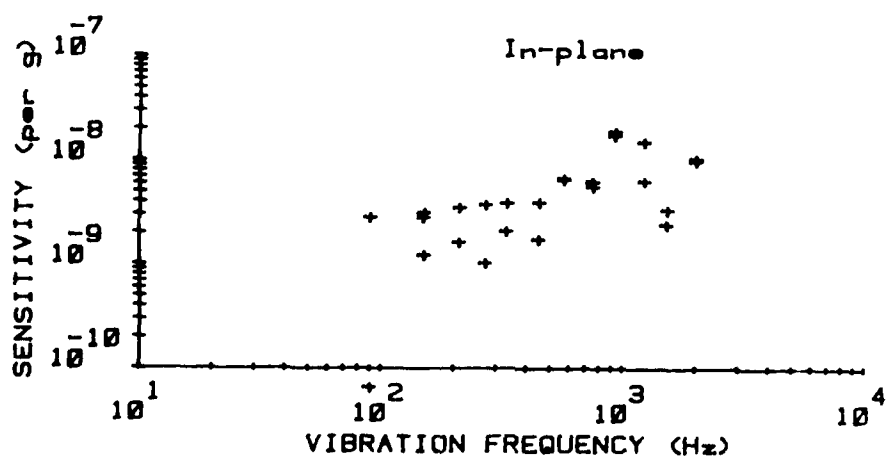
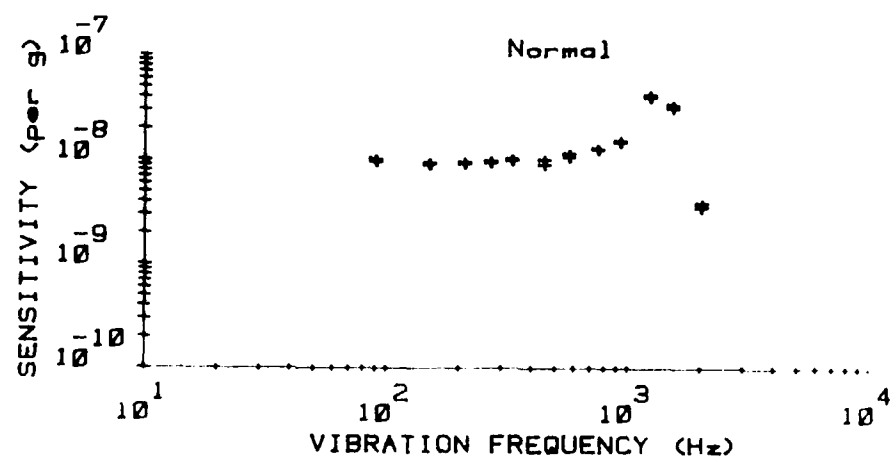


Figure 2. Sample experimental data.

$$\frac{\delta\Gamma}{\Gamma} = \frac{-\epsilon}{\phi + \epsilon}, \quad (7)$$

In equations (5) thru (7),  $\epsilon$  refers to the error in the measurand of interest, and  $\phi$  in equation (7) refers to the measurand itself. For the measurement system as implemented here, the dominant source of error is the sideband power ratio measurement which limits the measurement of  $|\Gamma|$  to +19/-16% accuracy.

## EXPERIMENTAL RESULTS

Sample data obtained using the measurement system are shown in Figure 2. The maximum and minimum values obtained at each acceleration frequency tested are shown as a function of the test frequency. The labels "Normal" and "In-plane" refer to measurements normal to the plane of the SAW resonator and in the plane of the SAW resonator respectively. In this device we observe a mechanical mounting related resonance near 1kHz which degrades net device sensitivity by up to a factor of five in the resonance region. We also observe that the mounting technique used produces greater repeatability normal to the plane of the SAW as compared to in the plane of the SAW. The results of all the delay line measurements are summarized in Table 2 and the results of the resonator measurements are summarized in Table 3.

## INFLUENCE OF FABRICATION PARAMETERS

The results obtained on the two-port resonators may be used to study the influence of certain fabrication parameters on SAW device acceleration sensitivity, although caution is advised in drawing conclusions from a small sample lot.

TABLE 2. DELAY LINE ACCELERATION SENSITIVITY

S/N	Normal	In-plane	Total
Q1359A	$2.2 \times 10^{-8}$	$6.0 \times 10^{-9}$	$2.5 \times 10^{-8}$
Q1359#2	$2.2 \times 10^{-8}$	$8.0 \times 10^{-9}$	$2.5 \times 10^{-8}$
Q1357A	$1.4 \times 10^{-8}$	$< 1.0 \times 10^{-8}$	$1.6 \times 10^{-8}$
Q1357B	$1.4 \times 10^{-8}$	$< 2.0 \times 10^{-8}$	$2.5 \times 10^{-8}$
Q1357C	$1.8 \times 10^{-8}$	$< 2.0 \times 10^{-8}$	$2.8 \times 10^{-8}$
Q1398A	$2.1 \times 10^{-8}$	$< 9.0 \times 10^{-9}$	$2.1 \times 10^{-8}$
Q1398B	$1.2 \times 10^{-8}$	$< 2.0 \times 10^{-8}$	$3.0 \times 10^{-8}$
Q1402D	$2.2 \times 10^{-8}$	$< 2.0 \times 10^{-8}$	$3.0 \times 10^{-8}$
Q1816A	$1.0 \times 10^{-8}$	$< 2.0 \times 10^{-8}$	$2.0 \times 10^{-8}$
Q1816B	$4.5 \times 10^{-9}$	$< 1.4 \times 10^{-8}$	$1.4 \times 10^{-8}$
Q1816C	$9.0 \times 10^{-9}$	$< 1.0 \times 10^{-9}$	$1.4 \times 10^{-8}$
Q1817F	$5.0 \times 10^{-9}$	$< 5.0 \times 10^{-8}$	$5.0 \times 10^{-8}$

TABLE 3. RESONATOR ACCELERATION SENSITIVITY

Type	S/N	Normal	In-plane	Total	Comment
One-Port	Q1758-7	$1.2 \times 10^{-8}$	$2.5 \times 10^{-9}$	$1.2 \times 10^{-8}$	baseline
Two-Port	Q1773-6	$2.5 \times 10^{-8}$	$1.2 \times 10^{-9}$	$2.5 \times 10^{-8}$	Cu-Al
Two-Port	Q1773-9	$2.1 \times 10^{-8}$	$2.0 \times 10^{-9}$	$2.1 \times 10^{-8}$	Cu-Al
Two-Port	Q1823D	$1.4 \times 10^{-8}$	$5.5 \times 10^{-9}$	$1.5 \times 10^{-8}$	10,000Å busbars
Two-Port	Q1824A	$< 2.0 \times 10^{-8}$	$5.0 \times 10^{-9}$	$5.0 \times 10^{-9}$	800Å transducers
Two-Port	Q1825A	$< 4.0 \times 10^{-9}$	$4.0 \times 10^{-9}$	$4.0 \times 10^{-9}$	10,000Å busbars
Two-Port	Q1825D	$< 6.0 \times 10^{-9}$	$6.0 \times 10^{-9}$	$8.0 \times 10^{-9}$	10,000Å busbars
Two-Port	Q1826B	$9.0 \times 10^{-9}$	$2.0 \times 10^{-9}$	$9.0 \times 10^{-9}$	10,000Å busbars
Two-Port	Q1826D	$9.0 \times 10^{-9}$	$< 2.5 \times 10^{-9}$	$9.5 \times 10^{-9}$	10,000Å busbars
Two-Port	Q1829A	$9.5 \times 10^{-9}$	$< 2.2 \times 10^{-9}$	$9.5 \times 10^{-9}$	400Å transducers

Figures 3 thru 5 show the variations in  $|\Gamma|$  as a function of busbar thickness for units with 600Å thick transducers, including two units with Cu-doped Al transducers. We observe that as the busbar thickness is increased, the in-plane acceleration sensitivity is increased while the normal acceleration sensitivity is decreased, with the rate of improvement in normal sensitivity slightly larger than the rate of degradation of in-plane sensitivity. The in-plane sensitivity is typically less than the normal sensitivity for the units tested here. The trend implied by the data is for equal in-plane and normal components at a busbar thickness slightly in excess of 10,000Å.

Figures 6 thru 8 show the variations in  $|\Gamma|$  as a function of transducer thickness for units with 2000Å thick busbars, including two units with Cu-doped Al transducers. Without further experimental samples, it is difficult to determine whether any trends are present or whether the large differences in  $|\Gamma|$  between units with Al transducers and those with Cu-doped Al transducers are due to the metallization differences.

## DISCUSSION

The devices tested here were developed for a low-noise radar application. The quiescent phase noise among the two-port devices of the various metallization types varied by 3dB, whereas the acceleration induced phase noise varied by 16dB. Unpublished data [2] indicating similar effects of similar magnitude for bulk wave plate resonators have recently been confirmed and theoretical models for the effect proposed [3-5]. Based on the theoretical and experimental work to date, it is suggested that careful control of transducer and busbar metallization may be used to optimize for acceleration induced phase noise without seriously compromising quiescent phase noise.

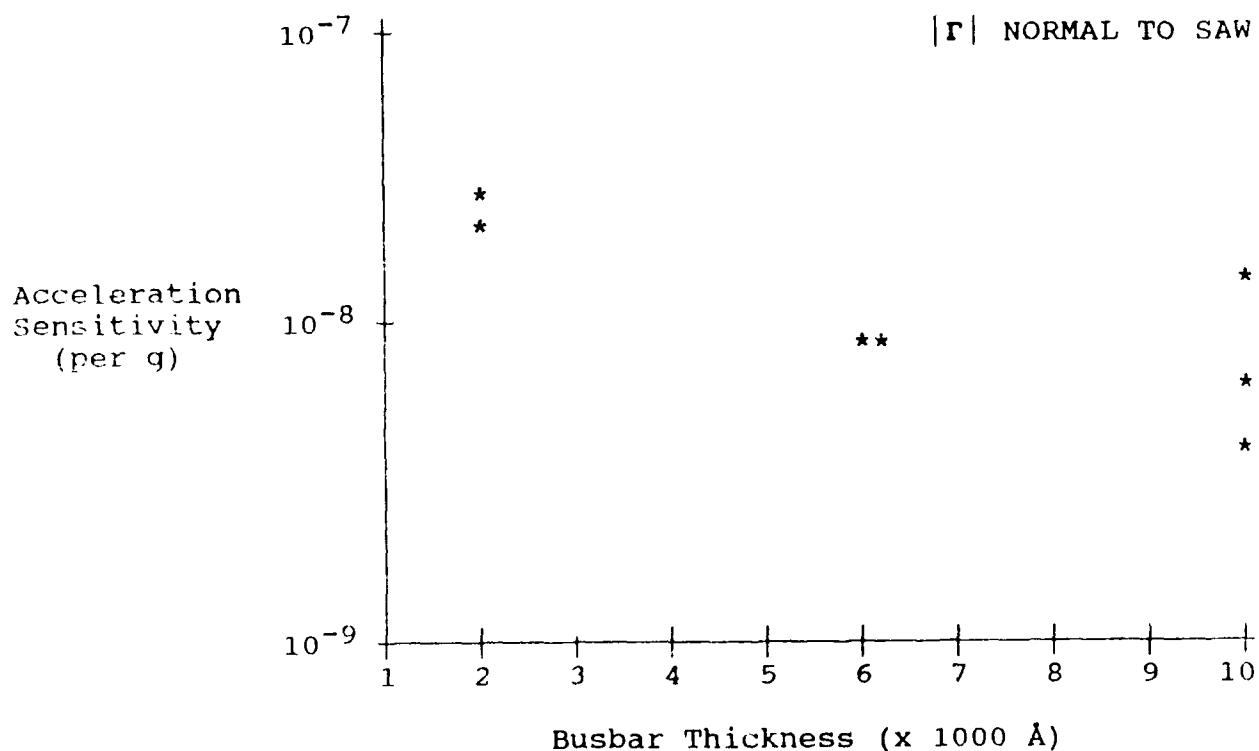


Figure 3. Two-port resonator acceleration sensitivity normal to the plane of the SAW device versus busbar thickness.

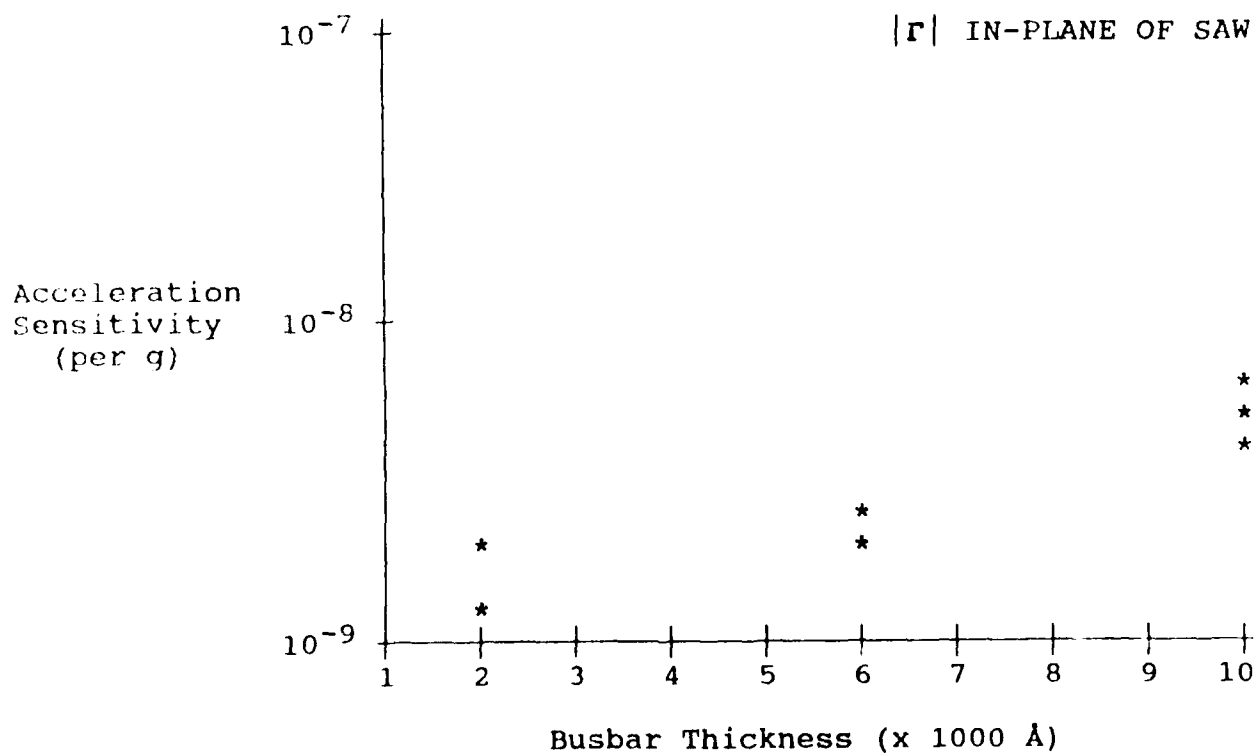


Figure 4. Two-port resonator acceleration sensitivity in the plane of the SAW device versus busbar thickness.

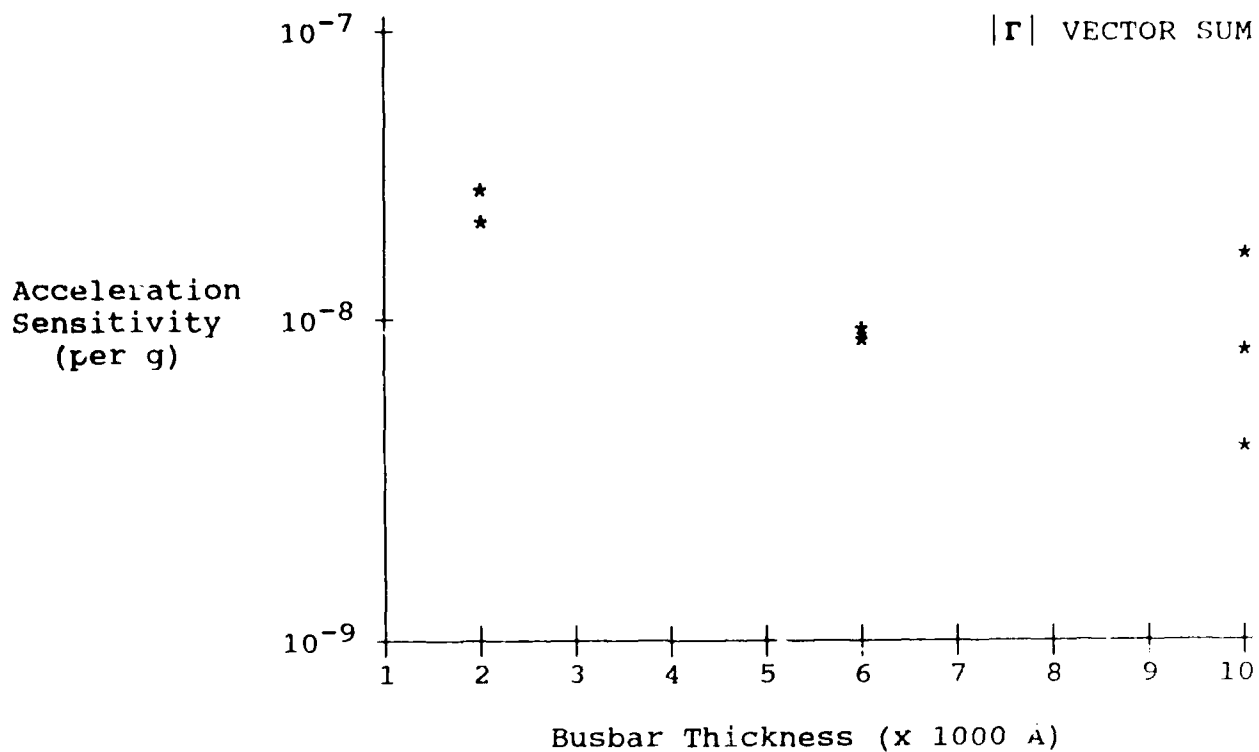


Figure 5. Two-port resonator acceleration sensitivity net vector sum versus busbar thickness.

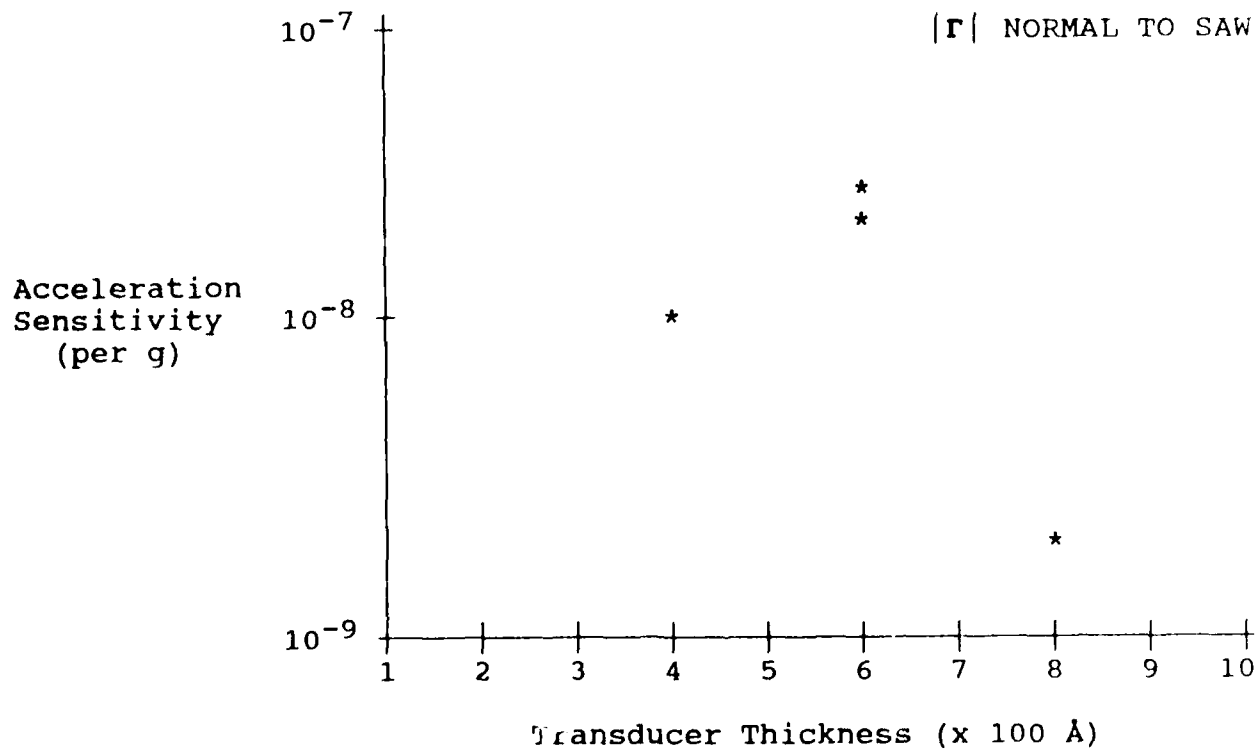


Figure 6. Two-port resonator acceleration sensitivity normal to the plane of the SAW device versus transducer thickness.

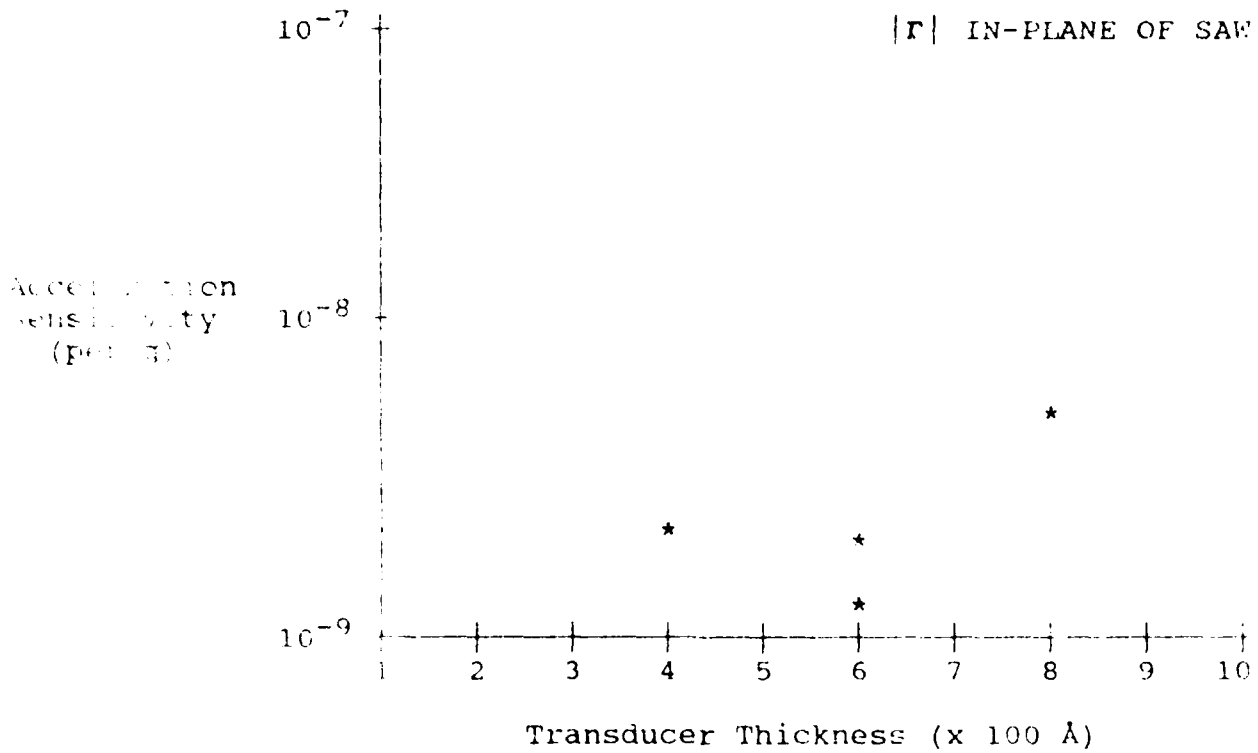


Figure 1. Two-port resonator acceleration sensitivity in the plane of the SAW device versus transducer thickness.

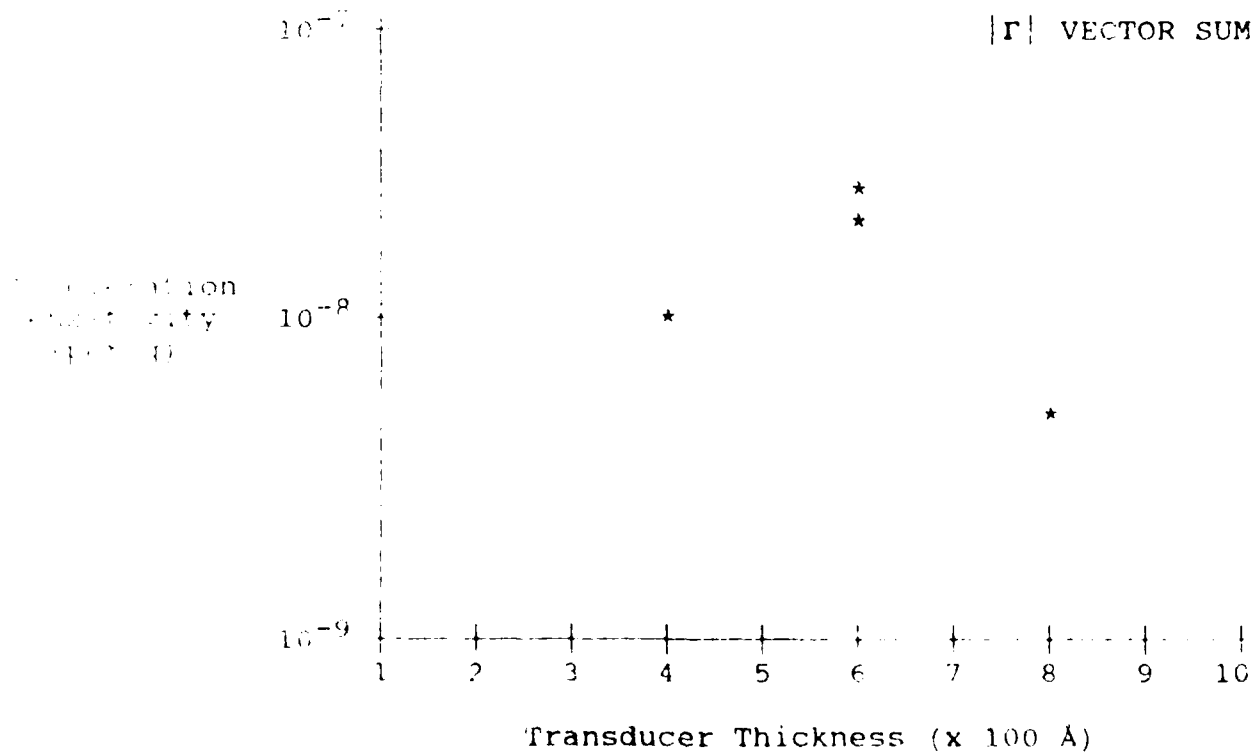


Figure 2. Two-port resonator acceleration sensitivity net vector versus transducer thickness.

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